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Publication date:
1998

Document Version
Publisher's PDF, also known as Version of record

AAU Geotechnical Engineering Papers

ISSN 1398-6465 R 9803

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February 1998

Soil Mechanics Paper No 21

GEOTECHNICAL ENGINEERING GROUP
AALBORG UNIVERSITY DENMARK

Ibsen, L.B. (1998). Advanced Numerical Analysis of Caisson Breakwater.

AAU Geotechnical Engineering Papers, ISSN 1398-6465 R9803.

Soil Mechanics Paper No 21

2nd PROVERBS Workshop, Napels, February 24-27-98.

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Advanced Numerical Analysis of Caisson Breakwater

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"Constitutive Modelling of Baskarp sand" was the title and issue dealt with in MAST III report (Andersen et al 1997). Among other things, the Single Hardening Model was introduced and investigated with the purpose of evaluating its capability of predicting the behaviour of frictional materials observed in triaxial tests. In this way, the verification of the Single Hardening Model has until now only been based on predictions of conventional triaxial tests compared to actual test results. Therefore, the aim of this work (fully reported in the MAST III report /Andersen et all 1997.a/) has been to investigate the applicability of the Single Hardening Model for solving geotechnical problems of a more complex nature.

Calibration of the Model

It was concluded in Andersen et al. (1997) that in connection with the calibration of the Single Hardening Model, initiatives should be taken in order to improve the calibration. At that time, a parameter calibration for Baskarp Sand No. 15 with void ratio, e = 0,61 was performed, and it was concluded that especially in connection with the yield surface parameter, h and the variation of the yield surface parameter, q with respect to stress level, S, diverging results were obtained in comparison with the assumptions of the Single Hardening Model. It turned out that these parameters influenced the quality of the performed predictions of triaxial compression tests highly. Therefore, there is put a great effort into the investigation of a possible improvement of the parameter calibration.

Thus, additional triaxial tests have been carried out on Baskarp Sand No. 15 and Eastern Scheldt Sand as shown in (Andersen et all 1998.b) in order to support the study of the calibration parameters. Besides providing a solid basis for the parameter study, the triaxial tests serve to elucidate the general behaviour of sand. In this way, it is stated that Eastern Scheldt Sand supports the characteristic state theory. Furthermore, the behaviour observed during large stress reversals has been subjected to an analysis. Performing un- and reloading cycles it was observed that plastic strains were present, in contrast with the theory of the Single Hardening Model where purely elastic behaviour during a load cycle is assumed. However, performing un- and reloading cycles down to 50 percent of the maximum shear stress, purely elastic behaviour was indeed observed. This supports the presence of the Bauschinger effect and questions the applicability of the Single Hardening Model, if a precise description of large un- and reloading cycles is wished for. Finally, the assumption of isotropic soil behaviour has been investigated, as this is a fundamental assumption made by the Single Hardening Model. Thus, the slopes of the volumetric strain curves from hydrostatic compression tests have been considered. It was found out that some scatter is present, as the slopes differ slightly from the required slope of 1 in 3. The scatter is put down to experimental uncertainties.

Parameter calibrations have been carried out in the same manner as introduced in Andersen et all (1997). Similar tendencies were observed, as especially the yield surface parameter, h and the q,S variation are encumbered with some deviation relative to the assumptions of the Single Hardening Model. Therefore, initiatives have been taken in order to improve the parameter calibrations in general.

First and foremost, the observed deviation relative to isotropic soil behaviour during hydrostatic compression has been investigated. Thus, a determination of the hardening parameters based on ε_1 , only, was carried out. It has turned out that in this way, the variation of the yield surface parameter, h with respect to the confining pressure becomes less pronounced. Thus, a clear improvement of the triaxial test predictions was observed and therefore it has been chosen to base the entire parameter determination on this assumption. Still, the suggested q,S variation has been seen to capture the experienced variations inadequately, which has given rise to the development of alternative proposals for the q,S expression. The first attempt resulted in a modified hyperbolic expression calibrated on the basis of the characteristic state. However, the modified hyperbolic expression has been seen to be numerically unstable in a general FEM description. As a numerically stable alternative, a sinusoidal expression was developed, whereby a better reconstruction of the q,S variation for all materials is possible. Considerable deviations are still experienced for Baskarp Sand No. 15 at the smallest void ratios. It has been concluded that the best predictions are obtained using the sinusoidal expression combined with a reduced value of the initial slope of the softening curve.

The remaining model parameters have been investigated as well, in order to estimate the influence of a change of these parameters to the numerical predictions. In that way it has been concluded that the influence of a change of the elastic parameters is insignificant as long as the parameters are chosen within a reasonable range. For triaxial test predictions, the same observation is present for the parameter, ψ_1, which governs the shape of the plastic potential- and yield surfaces in the octahedral plane. This parameter is determined on the basis of the failure parameter, m. The remaining plastic potential parameters, ψ_2 and μ have been seen not to influence the stress-strain behaviour. However, evaluating the predicted volumetric strain curves, the change of these parameters is clearly registered. It should be noted that no attempt has been done in order to modify the failure parameters, as these parameters are generally determined on a firm basis.

Finally, a void ratio dependency formulation has been put forward on the basis of the parameters determined from the tests in the database. As additional reference, data determined for Monterey No. 0 Sand, and Sacramento River Sand have been brought in. On the basis of the limited amount of data it is observed that a coherence between the parameters and the void ratio is present, although quite some scatter is present.

Summing up, it is stated that the below listed issues are considered to be essential in order to achieve numerical predictions of the highest quality:

1. In general, the experimental behaviour of Eastern Scheldt Sand is captured the best by the numerical predictions. One of the significant differences between the tests performed on Baskarp Sand No. 15, and the tests on Eastern Scheldt Sand is a smaller amount of pre-consolidation during preparation for Eastern Scheldt Sand. As the development of plastic work is essential to the parameter determination, it is believed that it is important to carry out the preparation of the test specimens at the lowest possible vacuum in order to prevent a high rate of pre-consolidation.

2. Furthermore, it is advised to plan the performance of the triaxial tests in such a manner that the parameter calibration is supported by reliable test results. Thus, a hydrostatic compression test to a high level of confining pressure is an absolute must in order to determine reliable hardening parameters. It has moreover been observed that a hydrostatic un- and reloading cycle supports the determination of the elastic parameters quite well in terms of the bulk modulus.

3. In order to estimate reliable data for Poisson's ratio, it is required that the triaxial tests are performed at constant confining pressure.

4. At least three drained triaxial tests must be performed over a wide range of confining pressures. The tests should include un- and reloading cycles after peak failure.

5. The hardening parameters should be estimated on the basis of the assumption of isotropic soil behaviour.

6. Finally, the newly described sinusoidal expression together with an initial slope of the softening curve equal to 0,8 provide significantly better predictions of the experimentally observed behaviour.

Taking these issues into account it is believed that it is generally possible to optimise the Single Hardening Model in order to provide reliable numerical predictions.

Numerical Investigations

Until this point, the constitutive behaviour defined by the Single Hardening Model has been employed for predictions of triaxial tests, exclusively. For use in a general problem, however, the Single Hardening Model must be linked with a finite element program. Therefore, the constitutive model has been implemented in a subroutine working together with the finite element program ABAQUS.

In order to ensure that reliable results are obtained when using the material model subroutine for actual calculations, the implementation has been verified. During the verification process it was experienced that the implemented version of the model was unable to handle certain situations in a proper manner. Thereby, the necessity of obtaining knowledge regarding the actual implementation arose. In this way, great emphasis has been laid on investigating the material model subroutine in order to solve the problems encountered during the verification process. As a particular interesting issue, the concept of strengthening of a material due to preshearing was investigated. It appeared that the implemented version of the Single Hardening Model is in fact capable of handling the concept of preshearing, although still some unanswered questions are present. In this way, it has been observed that in the case of preshearing, the consistency condition, which is an essential part of an elasto-plastic formulation is no longer fulfilled. In order to solve this problem, intensive investigations of this particular issue must be carried out, which however fall outside the scope of the work in (Andersen et all 1998.a)

On the basis of the verified version of the material model subroutine, the response of a gravity caisson breakwater has been subjected to a numerical analysis. As one out of several bases for comparison, the results from a centrifuge test performed at Delft Geotechnics have been brought in. In order to ensure reliable use of the test results, emphasis has been laid on acquiring knowledge regarding the special technique of centrifuge testing. The application of the caisson dead load in the caisson is carried out by accelerating the centrifuge to the chosen level of gravitational acceleration. This acceleration process has been compared with a corresponding numerical analysis, based on the Single Hardening Model. An observed deviation between the experimental and numerical behaviour has been put down to experimental uncertainties, together with an uncertain constitutive description at very low stress levels.

The drained bearing capacity due to horizontal loading of the caisson breakwater as predicted by the Single Hardening Model is compared with the bearing capacity obtained from an analytical analysis based on a kinematically admissible rupture figure. Furthermore, an analysis based on the bearing capacity formulation of Terzaghi has been carried out. A clear resemblance between the bearing capacity obtained on the basis of the Single Hardening Model and the analytically calculated bearing capacities has been experienced.

As an additional reference, predictions of the drained response of the caisson breakwater, based on the much simpler linear Drucker-Prager Model have been carried out. The employed version of the Drucker-Prager Model is the linear elastic, perfectly plastic model. It has been experienced that the response of the caisson is highly dependent of the used input parameters, as quite distinct results can be obtained, although the chosen parameters are considered to be relevant for the material in question. In this way, it must be stated that if the linear Drucker-Prager Model is to be used at all, it is essential to be able to provide a reasonable estimate on the stress state in the soil in order to apply the correct strength parameters for the analysis in question. The movements of the caisson predicted by the Single Hardening Model, and the Drucker-Prager Model, respectively, have been seen not to coincide. The predictions by the Drucker-Prager Model are considered to describe the situation inadequately, due to the assumption of linear elastic, perfectly plastic soil behaviour.

The response of the caisson when exposed to load cycles of varying magnitude has been investigated by the Single Hardening Model as well. Furthermore, the dependency of the void ratio has been analysed. In both cases, the predicted response is considered reasonable.

During the centrifuge test, the caisson breakwater is exposed to several impact loads of a large magnitude, in order to simulate a storm situation. As an estimate on the response of the caisson in this situation, a numerical analysis including the pore fluid response has been carried out by the Single Hardening Model. The horizontal bearing capacity obtained from this analysis is larger than the corresponding drained prediction, which is due to a negative pore pressure build-up in the soil layer. A nice correspondence between the numerically predicted bearing capacity, and the maximum force experienced in the centrifuge test has been observed.

The failure mechanisms observed from the respective numerical analyses have formed the basis of a visual comparison. In all cases, a fully developed rupture zone, concentrated around the corner of the caisson, opposite to the load application point, is experienced. This behaviour is in correspondence with the rupture figure considered in connection with the analytical upper bound solution. Furthermore, the numerically predicted displacement fields are similar to the displacement field considered in the analytical analysis.

Regarding the computational efficiency of the respective numerical analyses, it should be mentioned that large differences have been experienced regarding the time needed for the analyses. In this way, the predictions based on the Single Hardening Model have been observed to require considerably more computational power than the corresponding Drucker-Prager analyses. It should be kept in mind, however, that due to the linear-elastic, perfectly plastic behaviour assumed by the Drucker-Prager Model, the number of calculations within each increment is small compared to the corresponding Single Hardening Model prediction, as this model includes hardening plasticity. Still, it would be preferable if it was possible to increase the computational efficiency of the subroutine containing the Single Hardening Model. Actually, this is considered to be a necessity if it is desired to be able to model a general three dimensional prototype structure. This statement is based on the fact that during the verification of the material model subroutine, the response of a simple shear test has been predicted by means of three dimensional elements. Even though the number of elements of the model is no higher than 400, the required computational time is extremely extensive. For modelling a general three dimensional structure, the required number of elements would be considerably higher. A possible point of effort regarding an improvement of the efficiency of the routine could be a change of the stress updating procedure, which is currently based on the forward Euler scheme.

Still, it must be emphasised that use of an advanced constitutive model like the Single Hardening Model is bound to require great efforts as regards to the calibration of the model, as well as the computational power needed for the actual analysis. Therefore, the relevance of applying such advanced model for solution of a geotechnical problem must be judged on the basis of the character of the problem considered. Hence, if e.g. only the drained bearing capacity of a given structure is desired, a simple analytical solution is considered to provide sufficiently precise results, meaning that in such cases application of a complex constitutive model is far from necessary. On the other hand, if the actual stress-strain response of the considered material is important to the results, as e.g. when the pore pressure build-up in the soil is essential, the use of a constitutive relation, which is able to capture the actual soil response is indeed relevant. On the basis of the analyses performed throughout this thesis, it is stated that the Single Hardening Model is at this point ready for application in such types of geotechnical problems.

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